THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine
Aeronautics and Space Engineering Board
Space Studies Board

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July 13, 2004

The Honorable Sean O'Keefe
Administrator
National Aeronautics and Space Administration
Washington, DC 20546-0001

Dear Mr. O'Keefe:

At the request of the National Aeronautics and Space Administration, the National Research Council recently established the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope.[1] The committee's statement of task charges it to assess the viability of a shuttle servicing mission, evaluate robotic and ground operations to extend the life of the telescope as a valuable scientific tool, assess telescope component failures and their impact, and provide an overall risk-benefit assessment of servicing options.[2] The statement of task includes the possibility of transmitting an interim report to NASA prior to the submission of a final report.

The committee thanks you very much for your generous allocation of time in meeting with it on June 22, 2004. The information that you conveyed on the decision-making process that you and NASA followed when arriving at the Hubble-related decisions in January and in March 2004 was very important for us to hear directly from you. The additional information that you provided on NASA activities related to the shuttle return-to-flight program and robotic engineering in the broader context of long-term human space exploration was very useful, as was the extensive question-and-answer dialog that you enthusiastically engaged in with the committee.

Because you and your NASA colleagues have made clear to the committee that there is some urgency in issuing any recommendations related to Hubble, we are providing you with this interim report.[3] It offers three principal findings and recommendations. These are based on the committee's collective knowledge as well as input from other experts, both internal and external to NASA. This interim report does not address any one request in the statement of task in its entirety, but rather touches on aspects of task components 1, 2, and 4. Here the committee considers the degree of importance that a Hubble servicing mission would have for science, as well as some of the key factors involved in selecting a servicing mission option. Its aim is to provide useful guidance to NASA that can be utilized during the time that the committee (as well as NASA) continues to investigate the servicing options in greater detail. The work of the committee will continue during the coming weeks, and we expect to finish drafting a final report

[1] The committee roster is provided in enclosure A. Additional background material on the motivation for the study can be found in enclosure B.
[2] See the statement of task in enclosure B.
[3] Information about the independent review of the committee's report under the supervision of the NRC's Report Review Committee is provided in enclosure C.

by late summer or early fall. The final report will address in detail all four of the requests in the study's statement of task.

Importance of a Hubble Servicing Mission

The Hubble Space Telescope (HST) is arguably the most important telescope in history. Much of Hubble's extraordinary impact was foreseen when the telescope was being planned. It was predicted, for example, that the space telescope would reveal massive black holes at the centers of nearby galaxies, measure the size and age of the observable universe, probe far enough back in time to capture galaxies soon after their formation, and provide crucial keys to the evolution of chemical elements within stars.

All of these predicted advances have been realized, but the list of unforeseen Hubble accomplishments may prove even greater. Hubble did discover "adolescent" galaxies, but it also saw much farther back in time to capture galaxies on the very threshold of formation. Einstein's theory of general relativity was bolstered by the detection of myriad gravitational lenses, each one probing the mysterious dark matter that pervades galaxies and clusters of galaxies. Gamma-ray bursts had puzzled astronomers for more than 20 years; in concert with ground and X-ray telescopes, Hubble placed them near the edge of the visible universe and established them as the universe's brightest beacons, outshining whole galaxies for brief moments. Perhaps most spectacularly, Hubble confirmed and strengthened preliminary evidence from other telescopes for the existence of "dark energy," a new constituent of the universe that generates a repulsive gravity whose effect is to drive galaxies apart faster over time. The resulting acceleration of universal expansion is a new development in physics, possibly as important as the landmark discoveries of quantum mechanics and general relativity near the beginning of the 20th century.

Closer to home, Hubble has zeroed in on our own cosmic past by uncovering virtual carbon copies of how the Sun and solar system formed. Dozens of protoplanetary disks have been found encircling young stars in nearby star-forming regions of the Milky Way. The sizes and densities of these disks show how surplus dust and gas collect near infant stars to form the raw material of planets. Dozens of large, Jupiter-like planets have been discovered, initially by other telescopes but recently by Hubble using a new and more precise method. Measuring the tiny drop in light as a planet transits the disk of its parent star, the new technique could lead to a method for discovering Earth-like planets—a discovery with tremendous long-term implications for the human race.

Riveting as they are, these scientific returns from Hubble are far from their natural end. With its present instruments the telescope could continue probing star formation and evolution, gathering more data on planetary systems, revealing planetary and cometary phenomena in our own solar system, and exploring the nature of the universe at much earlier times. However, two new instruments, already built for NASA's next planned servicing mission (SM-4), would amplify the telescope's capabilities by allowing qualitatively new observations in two underexploited spectral regions. Such rejuvenation via new instruments has occurred after every Hubble servicing mission, and the next one promises to be no different. Wide Field Camera-3 (WFC3) would increase Hubble's discovery efficiency[4] for ultraviolet and near-infrared imaging by factors of 10 to 30. The UV channel coupled with the camera's wide field of view will image the final assembly of galaxies still taking place in the universe. The near-infrared channel of WFC3 favors discovery of the very youngest galaxies, whose light is maximally red-shifted. The available UV,

[4] Throughput multiplied by the area of the field of view.

visible, and near-IR channels will combine to give a sweeping, panchromatic view of objects as diverse as star clusters, interstellar gas clouds, galaxies, and planets in our own solar system.

The second new instrument, the Cosmic Origins Spectrograph (COS), will increase Hubble's observing speed for typical medium-resolution ultraviolet spectroscopy by at least a factor of 10 to 30, and in some cases by nearly two orders of magnitude. Ultraviolet spectra carry vital clues to the nature of both the oldest and the youngest stars, yet UV rays are totally invisible from Earth's surface. COS will fill important gaps in our understanding of the birth and death of stars in nearby galaxies. Even more impressive, COS will use the light of distant quasars to spotlight hitherto undetectable clouds of dispersed gas between nearby galaxies, thereby mapping in unprecedented detail the properties of the so-called "cosmic web."

FINDING. Compelling scientific returns will result from a servicing mission to the Hubble Space Telescope that accomplishes the scientific objectives of the originally planned NASA servicing mission SM-4.

RECOMMENDATION. The committee urges that NASA commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission, including both the replacement of the present instruments with the two instruments already developed for flight—the Wide Field Camera-3 and the Cosmic Origins Spectrograph—and the engineering objectives, such as gyroscope and battery replacements. Such a servicing mission would extend the life of this unique telescope and maximize its productivity.

Other potential options to extend the useful life of Hubble—for example, by servicing components such as batteries and gyroscopes but without replacing instruments—will be studied by the committee as part of its charge. However, such a reduced level of servicing has not been featured in the repair strategies that the committee has heard about to date. The scientific impacts of reduced levels of servicing below that envisioned in SM-4 will be considered in the committee's final report.

Servicing Mission Options

A wide range of factors must be considered when assessing the risk and effectiveness of HST servicing and deorbiting options. These options range from robotically attaching a deorbit module to Hubble to performing a mission (human or robotic) that replaces both scientific instruments and also services or repairs a number of engineering components. You discussed many of these options with us on June 22. One essential task is to enable the ultimate safe deorbiting of the spacecraft so that humans on Earth will not be at risk during its reentry. The present plan is to launch and robotically attach a deorbit module to the telescope around the year 2013.[5] Consistent with this plan, NASA issued a Request for Proposals (RFP) on June 1, 2004, for a Hubble disposal vehicle.[6]

Another risk concerns robotic servicing and possible replacement of telescope instruments. You told the committee that a robotic mission "will be really tough." NASA has proposed that a

[5] This is the earliest date at which Hubble would be expected to reenter the atmosphere without intervention.

[6] The RFP can be found at the following URL: http://www2.eps.gov/spg/NASA/GSFC/OPDC20220/HST%2DDM%2D0002%2DGDJ/listing.html.

deorbit module might be attached to the spacecraft at the time of robotic servicing, although the recently issued RFP does not specifically require either servicing or instrument replacement.[7]

The committee has been given detailed information on the plans for robotic servicing currently under consideration by NASA at its Goddard Space Flight Center. A subgroup of the committee visited Goddard and examined the current activities. The robotic servicing development effort at Goddard was officially initiated in 2004 and is a very recent undertaking. While considerable advances have been made in just a few months, there has been little time for NASA to evaluate and understand the technical and schedule limitations of robotic servicing.

The committee was gratified by your assurance that the robotic efforts will be adequately supported by the required resources in a timely manner. During the next year the robotic servicing mission project will have to achieve key milestones (including a critical design review in the summer of 2005) that will clarify the feasibility of a robotic servicing mission. Substantial resources will be required in Fiscal Year 2005 to accomplish this.

The committee finds the proposed robotic mission to be highly complex due to the inherent difficulties with supervised autonomy in the presence of time delays; the integration of vision and force feedback in six-degree-of-freedom assembly and disassembly tasks with high-degree-of-freedom, dexterous manipulators; and the coordinated control of the high-inertia HRV[8] with a long-reach robotic arm grappling with a high-inertia payload. Robotic emplacement of a deorbit module and replacement of instruments and subsystems on Hubble will require a rendezvous with a non-cooperative vehicle[9] together with a human in a telerobotic loop that has a substantial (on the order of 2-second) time delay.

The committee was informed about several current U.S. and foreign space programs that involve various concepts for robotic spacecraft rendezvous, capture, and servicing. Related U.S. experimental programs are currently scheduled for November 2004 (U.S. Air Force) and September 2006 (DARPA[10]). The committee has been informed that NASA is participating in some aspects of the DARPA program but this does not yet include a commitment to Hubble robotics servicing mission demonstrations. To the best of the committee's current understanding, difficult challenges of the Hubble robotic scenario (such as the time delay and a non-cooperative target) are not currently covered explicitly in either the Air Force or the DARPA programs. Based on information provided to the committee and the knowledge of members who have deep experience with shuttle flights and spacecraft servicing, the committee believes that the proposed robotic mission to Hubble will essentially be an experimental test program that is expected to accomplish specific programmatic objectives at the same time.

FINDING. The proposed Hubble robotic servicing mission involves a level of complexity, sophistication, and technology maturity that requires significant development, integration, and demonstration to reach flight readiness.

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[7] The RFP requires only submissions for a vehicle to provide end-of-life controlled reentry or other safe disposal of the HST; the RFP invites but does not require that submissions include life extension or servicing capabilities.

[8] Hubble Robotic Vehicle.

[9] A non-cooperative vehicle is a vehicle that is not equipped with transponders or active sensors, meaning that it cannot respond to electronic interrogation from other spacecraft or emit signals enabling its identification or localization.

[10] Defense Advanced Research Projects Agency.

RECOMMENDATION. As an early step, NASA should begin immediately to take an active partnership role that includes HST-related demonstrations in the robotics space experiments that are now under way in other agencies in order to ensure that the returns from these experiments can be beneficial to a potential robotic Hubble servicing mission.

The four HST shuttle servicing missions already completed have demonstrated that crew servicing and instrument replacement can be highly successful. Of course, there is risk to the astronaut crew in any human flight mission. As you informed the committee, some 25 to 30 additional shuttle missions are planned to complete the International Space Station (ISS). Based on its current assessment of the conclusions and recommendations contained in the Columbia Accident Investigation Board (CAIB) report[11] and the Stafford-Covey reports (latest dated May 19, 2004),[12] the committee concludes that a shuttle flight to the HST is not precluded by or inconsistent with the recommendations from these two NASA advisory groups.

The committee finds that the CAIB report makes clear distinctions between missions to the ISS and non-ISS missions. The CAIB report notes that the degree of difficulty is somewhat greater when conducting a non-ISS shuttle mission.[13] This is partially due to the fact that a non-ISS mission such as one to Hubble would not have as long a "safe haven" opportunity as would a mission docking with the space station. The shuttle repair capabilities at a non-ISS location would also be less robust than at the ISS itself. Even so, the CAIB report does not prescribe operational constraints on how to conduct a non-ISS mission, but rather only general risk mitigation steps that should be followed. The CAIB consciously accepted lower risk mitigation efforts for non-ISS missions (such as a mission to Hubble).[14]

The committee was cognizant and most appreciative of your extensive discussions with us related to the ownership that you, and NASA, have for the shuttle return-to-flight and for astronaut safety in the nation's civil space program. You stressed that total elimination of risk in crewed space flight is "impossible" and that you and NASA are "not risk averse." From information it has received, including the risk information to date, the committee concludes that there would be little additional investment in time and resources required over the next year for NASA to keep open an option for a human servicing mission to Hubble.

According to briefings received by the committee, the risk assessments for viable Hubble servicing alternatives, both human and robotic, have not yet been completed or reported by NASA. The Hubble project office is currently investigating risks associated with robotic mission scenarios. Additionally, the committee was told that probabilistic risk assessment results for shuttle flights should be available in the fall or winter of this year. Such a study will be important in improving the comparisons between the risks of human flights to the ISS and to Hubble.

FINDING. Because of inherent uncertainties in the early stages of development of a robotic mission to the Hubble Space Telescope, as well as the uncertain current status of the shuttle

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[11] Columbia Accident Investigation Board Report, Volume 1, August 2003, NASA and the Government Printing Office, Washington, D.C.
[12] Return to Flight Task Group Interim Report, January 20, 2004, and Return to Flight Task Group Second Interim Report, May 19, 2004.
[13] CAIB Report Recommendation R6.4-1, p. 174.
[14] Ibid.

return-to-flight program, the key technical decision points for committing to a specific service scenario are at least a year in the future.

RECOMMENDATION. At the same time that NASA is vigorously pursuing development of robotic servicing capabilities, and until the agency has completed a more comprehensive examination of the engineering and technology issues, including risk assessments related to both robotic and human servicing options, NASA should take no actions that would preclude a space shuttle servicing mission to the Hubble Space Telescope.

We would be pleased to brief you and your staff regarding the views expressed in this letter. We remain committed to completing our final report in an expedited fashion.

Sincerely,

Louis J. Lanzerotti, *Chair*
Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

Enclosures:

A Membership roster of the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope (as of July 2004)
B Project Overview
C Acknowledgement of Reviewers

cc: Edward J. Weiler, Associate Administrator, Office of Space Science, NASA
Craig E. Steidle, Associate Administrator, Office of Exploration Systems, NASA
William F. Readdy, Associate Administrator, Office of Space Flight, NASA
Lennard A. Fisk, Chair, Space Studies Board
William W. Hoover, Chair, Aeronautics and Space Engineering Board
Joseph K. Alexander, Director, Space Studies Board
George Levin, Director, Aeronautics and Space Engineering Board

Enclosure A

Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

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JOHN M. KLINEBERG, Space Systems/Loral (retired), Redwood City, California
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Enclosure B

Project Overview

Background

The Hubble Space Telescope was originally launched aboard the space shuttle in 1990, with a designed mission lifetime of 15 years. Since then the telescope has been repaired or upgraded four times, each requiring a very complex, dedicated space shuttle mission and unique HST servicing support equipment. Over its lifetime, HST has been an unprecedented scientific success, having earning extraordinary scientific and public recognition for its contributions to all areas of astronomy. Prior to the accidental loss of the space shuttle Columbia and crew in February 2003 there had been plans for another shuttle servicing mission, designated SM-4, to replace aging spacecraft batteries and gyroscopes and to install two new science instruments on the telescope.

Following the Columbia accident, the Columbia Accident Investigation Board (CAIB) was created to determine the cause of the accident and to advise NASA about steps to prevent future accidents. In its August 2003 report, the CAIB noted the inherent risk in any form of human space flight, and it made 29 recommendations, 15 of which were required to be completed before the space shuttle could return to flight. The report made specific recommendations about on-orbit inspections and repairs, and it noted differences between future flights to the International Space Station (ISS), which could be used as a safe haven, and other possible destinations. NASA subsequently formed an internal committee, called the Stafford-Covey Return-to-Flight committee, to provide advice about how to implement the CAIB recommendations and any other related actions. NASA Administrator Sean O'Keefe committed the agency to following all recommendations from both groups.

In mid-January 2004 Mr. O'Keefe announced that, as a consequence of safety considerations, NASA would reduce its shuttle manifest to only the 25 planned missions to the ISS. The decision was also made, on the basis of risk, to not pursue SM-4, but instead to investigate other options to extend the life of HST. Following that announcement Senator Barbara Mikulski asked O'Keefe to seek an independent opinion on whether the decision was, in fact, required to comply with the CAIB recommendations, and O'Keefe asked the CAIB chair, Adm. Harold Gehman, to review the matter. In his March 5, 2003, letter to Mikulski, Gehman said that "the Board is split on the merits of flying this mission." He also indicated that "whether to fly another mission to the Hubble is one of the public policy debates this nation should have," and he called for a "deep and rich study of the entire gain/risk equation (to) answer the question of whether an extension of the life of (HST) is worth the risks involved."

O'Keefe subsequently asked the National Academies for the study.

NASA plans to continue operation of the HST until it can no longer support scientific investigations—currently anticipated to occur in the 2007-2008 time frame. The telescope's life may, in fact, be extended if NASA is successful in employing operational techniques to preserve battery and gyroscope functions. Meanwhile, NASA is investigating innovative ways to extend the science lifetime of the HST for as long as possible, including robotic servicing. Current plans are to safely de-orbit HST by means of a robotic spacecraft by approximately 2013.

Statement of Task

The committee will conduct an independent assessment of options for extending the life of the Hubble Space Telescope. The study will address the following tasks:

1. Assess the viability of a space shuttle servicing mission that will satisfy all recommendations from the CAIB, as well as ones identified by NASA's own Return-to-Flight activities. In making this assessment, compare the risks of a space shuttle servicing mission to HST with the risks of a shuttle mission to the ISS and, where there are differences, describe the extent to which those differences are significant. Estimate to the extent possible the time and resources needed to overcome any unique technical or safety issues associated with HST servicing that are required to meet the CAIB recommendations, as well as those from the Stafford-Covey team.

2. Survey other available engineering options, including both on-orbit robotic intervention and optimization of ground operations, that could extend the HST lifetime.

3. Assess the response of the spacecraft to likely component failures and the resulting impact on servicing feasibility, lost science, and the ability to safely dispose of HST at the end of its service life.

4. Based upon the results of the tasks above, provide a benefit/risk assessment of whether extension of HST service life, via (a) a shuttle serving mission if one is deemed viable under task #1 and/or (b) a robotic servicing mission if one is deemed viable under task #2, is worth the risks involved. The assessment should include consideration of the scientific gains from different options considered and of the scientific value of HST in the larger context of ground and space-based astronomy and science more broadly. Special attention should be paid to the practical implications of the limited time available for meaningful intervention robotically or via the shuttle.

The committee is not expected to make either organizational or budgetary recommendations, but it may need to consider cost as a factor in weighing the relative benefits of alternative approaches.

The committee will investigate the possibility of providing an interim report to NASA that addresses a portion of the items in the task statement in advance of delivering a full final report if such an approach is deemed feasible and able to provide early, credible answers to the questions being considered.

Enclosure C

Acknowledgement of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Roger Blandford, Stanford University,
Wendy Freedman, Observatories of the Carnegie Institution,
Takeo Kanade, Carnegie Mellon University,
George Paulikas, The Aerospace Corporation (retired),
Harvey Tananbaum, Smithsonian Astrophysical Observatory,
Kathryn Thornton, University of Virginia,
Chris Whipple, ENVIRON International Corporation, and
Peter Wilhelm, Naval Research Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by William Press, Los Alamos National Laboratory, and John Ahearne, Sigma Xi. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.